N81 30532 D7

HEAT PIPE SOLAR RECEIVER WITH THERMAL ENERGY STORAGE

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ABSTRACT

A heat pipe solar receiver (HPSR) Stirling engine generator system featuring latent heat thermal energy storage, excellent thermal stability and self regulating, effective thermal transport at low system Δ T is described. The system has been supported by component technology testing of heat pipes and of thermal storage and energy transport models which define the expected performance of the system. Preliminary and detailed design efforts have been completed and manufacturing of HPSR components has begun. The modification of a Stirling engine for operation on condensing sodium vapor is required during 1981 in order that the system can be committed to a solar test at an early date. Additional developments will include the later design, construction and test of a flame impingement combustor which can be directly added to the existing system without major modifications. A progressive development of this first prototype toward low cost, mass production hardware is expected for wide solar applications.

SYSTEM DESCRIPTION

The heat pipe solar receiver with TES (HPSR) is a high efficiency solar receiver and thermal storage system for use as part of a self-contained 15-25 kW_e Stirling engine power conversion system located at the focal point of a parabolic dish concentrator and operating at an engine temperature of $\sim 1520^{\circ}F$. Its unique feature is the efficient collection, transport, storage and retrieval of solar energy through the use of high temperature sodium heat pipes and $NaF-MgF_2$ latent heat storage.

The concept of heat flow in the system and a conceptual design of an advanced development system are shown in Figures 1 and 2. The fourteen primary heat pipes in the receiver deliver heat through a bulkhead into a large secondary heat pipe containing (1) 73 capsules, each 2 inches in diameter and 33 inches in length and containing the eutectic fluoride TES salt, (2) a shell-side heat exchanger surface to accept heat from an efficient flame impingement combustor and (3) the heat exchanger tubes of a Stirling engine. The primary heat pipes transfer heat in one direction only to prevent heat loss from the TES. Heat transfer in the secondary heat pipe is effected in a near-isothermal manner by sodium vapor thermal transport without pumps, valves, controls or flow sensors; the hotter surfaces, such as the primary heat pipe, condensers or the combustor heat exchanger reject heat and the colder surfaces, where heat is being extracted, accept heat at near-isothermal temperatures. Differences in equilibrium vapor pressure within the system provide the driving force. Thus the system is self regulating in that the heat flow into and out of the system, the storage of energy in the latent heat salt and the provision of heat to

the engine are based upon minor temperature differentials occasioned by the operation of the system itself. Simple temperature instrumentation within the isothermal secondary heat pipe can indicate the subcooling or superheating of the TES; the temperature source for operation of the engine remains relatively stable varying only with the Δ T required to extract heat from the large surface area of TES material at low heat flux levels.

The small aperture of the receiver reduces convection and reradiation losses which results in high receiver efficiency.

The proposed flame impingement combustor on the TES shell features a high gas-side heat transfer coefficient approaching 120 Btu/hr-ft^2-^{o}F; sodium-side heat transfer coefficients are, of course, orders-of-magnitude higher. The technology of flame impingement combustors has been well advanced by Rasor Associates* through the development of large thermionic converters and through demonstrated improvements in combustors for Stirling engines using silicon carbide ceramic materials and advanced impingement combustor design techniques.

Other features of the advanced HPSR concept include the following. First, the all-stainless-steel construction made possible (1) by the use of dished heads on the secondary heat pipes to minimize the stresses from very low differential pressure within and outside this heat pipe and (2) by the use of sectioned-stiffened stainless steel forward and aft salt capsule support plates to carry axial loads from the salt capsules. Second, the development of reduced wicking requirements for supplying sodium with the TES. Third, improvement in Stirling engine efficiency from 39.6% to about 43% by engine heater head redesign to take advantage of improved sodium heat transfer coefficients at the heater tubes. This latter improvement in turn, decreases solar collection costs, improves TES storage time for equivalent weight and cost and results in less COE sensitivity to increase in fuel cost for the combustor assisted system. The general effects of these expected changes in efficiency and of the value of TES in increasing the ratio of solar-to-fossil fuel utilization are shown in Figure 3; results are based upon system performance and economic analysis over a one year period of simulated solar operation of hybrid Stirling solar systems.

SUPPORTING TECHNOLOGY

The technology of the HPSR is based upon well-founded heat pipe and latent heat storage data and experience and upon related heat pipe and latent heat storage developments for space applications. In addition, and specific to the present program, the primary heat pipe have been experimentally tested** in all operating attitudes as indicated in Figures 4 and 5.

*E.J. Britt, Rasor Associates, Inc., Sunnyvale, CA. 94086, Private Communication, October, 1980.

**Divakaruni, S.M., "Heat Pipe Design Confirmation Testing", DOE/JPL, 1060-27, GEAEP-55, September 25, 1979. See also Zimmerman, W.F., Divakaruni, S.M. and Won, Y.S., "Sodium Heat Pipe Use in Solar Stirling Power Conversion Systems", ASME 80-C2/S06-13 presented at ASME Century 2 Conference, San Fransisco, August 10-21-1980.

A modular TES experiment featuring a single primary heat pipe and a secondary heat pipe containing three standard design salt containers and a heat extraction coil to simulate the Stirling engine has been designed, built and tested at initial design heat flux conditions on the TES salt containers. This modular test apparatus was operated successfully at all operating angles in various modes of charging, discharging, direct heat through-put and mixed modes of operation. The test indicated the excellent thermal inertia of the system (less than 2°F/min. outside the latent heat range), low Δ T across heat pipes and isothermal operation of the secondary heat pipe. The components of the system and a typical TES charging curve are shown in Figures 6 and 7.

The above experimental effort has contributed significantly to the demonstration of the validity and expected performance demonstration of the thermal transport and storage concept.

SYSTEM DESIGN

During the past months a preliminary design has been submitted, modifications in that preliminary design have been made to accommodate, at a later date, the addition of the flame impingement combustor to the TES shell and a final detailed design has been prepared. This final design of a system using a United Stirling P40 engine and a 25 kW_e induction generator is shown in Figure 8. Sodium wicking is included inside the TES shell to permit internal heat transfer from the flame impingement combustor, which can be added at a later date. Other TES wicking includes arterial wicks which provide liquid sodium from a pool in the lower forward part of this large heat pipe; these wicks feed wire wicks on the surfaces of the primary heat pipe condensers and on the lower half of the TES salt containers. The upper half of the salt containers are supplied with sodium by gravity return from the engine through a diffusion bonded arterial wick at the rear salt container support plate and, thence, along wire wicks on the salt containers. Figure 9 shows these details.

The key characteristics of the prototype design, on which manufacturing work has just begun, is shown in Table 1. With about 0.8 hours of latent and sensible heat storage the entire system should weight about 2900 pounds. Higher engine and system efficiencies than those shown should be achieved with the modification of the P40 engine heater head for operation on condensing sodium vapor.

FUTURE EFFORTS

During the coming months the first prototype will be fabricated filled with sodium, thermally conditioned to assure that all the arterial wicks are filled and the capillary wicks are saturated with liquid sodium, the system will be shipped to Edwards Air Force Base in late summer 1981 for installation and solar test on the Test Bed Concentrator. A key element in the assembly and operation of this system is the availability of sodium heater head version of the P40 Stirling engine which is to be supplied by JPL for assembly with the HPSR prior to sodium filling. Work has not started yet on the modification

of the engine but is expected to begin soon. Thermal performance testing of the HPSR prior to solar operation would be desireable to check out the thermal transport and integrated operation of the receiver, TES and engine-generator. The development of the flame impingement combustor can be carried out separately and that combustor can later be mated with this prototype HPSR without modification to the interior of the secondary TES heat pipe. The test of the combustor on the HPSR could then be performed in either a factory test or a test on the solar concentrator. Finally, future design modifications and improvements will be required to minimize presently redundant wicking requirements and to introduce, in subsequent test hardware, lower cost components such as dished heads and alternative design support plates, etc.

The advantages of the excellent thermal transport, stable operating temperature and stored energy inherent in the HPSR are worthy of continued evaluation, exploitation and improvement, not only as these concepts apply to the Solar Stirling systems, but for the benefit of other high temperature solar energy systems, as well.

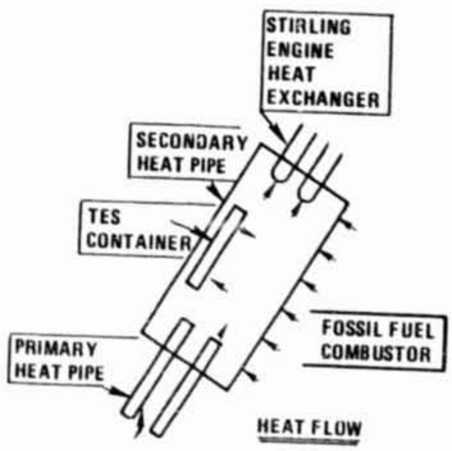

Figure 1. Schematic Diagram of Heat Flow in the HPSR

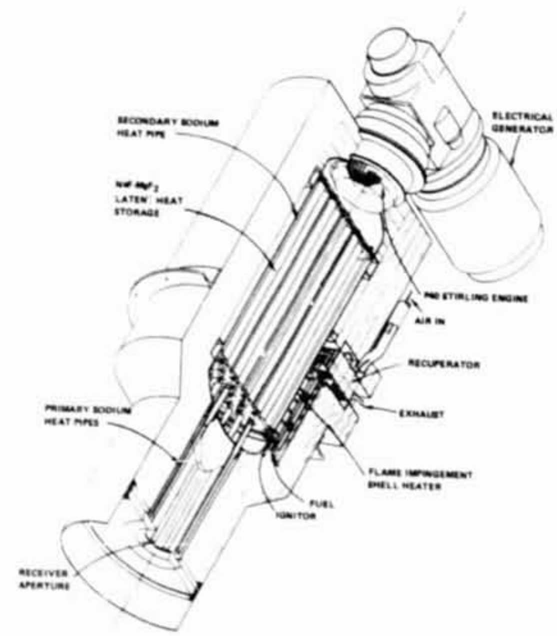

Figure 2. Advanced Development HPSR with Flame Impingement Fossil Fuel Combustor

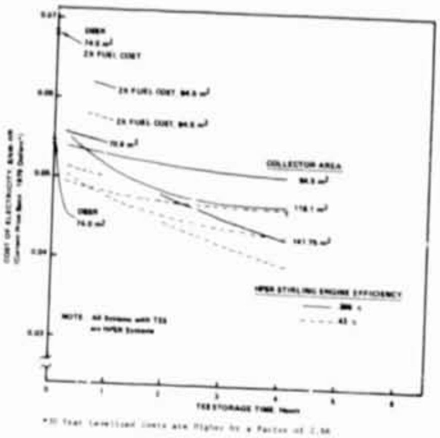

Figure 3. Cost of Electricity vs. TES Storage Time for Systems with Combustors

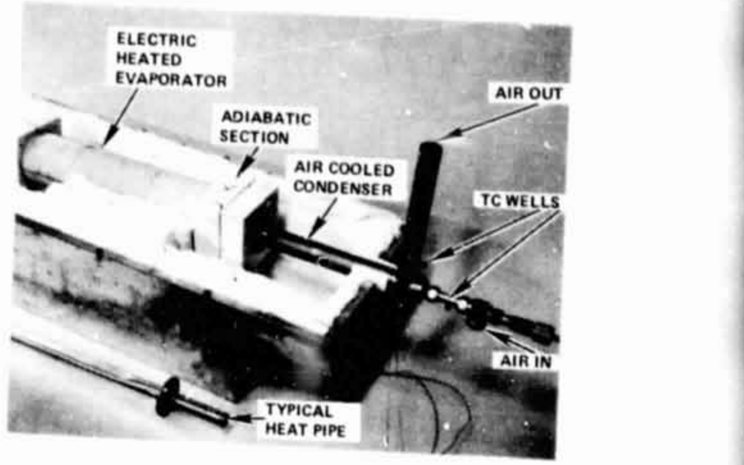

Figure 4. Heat Pipe Test Facility

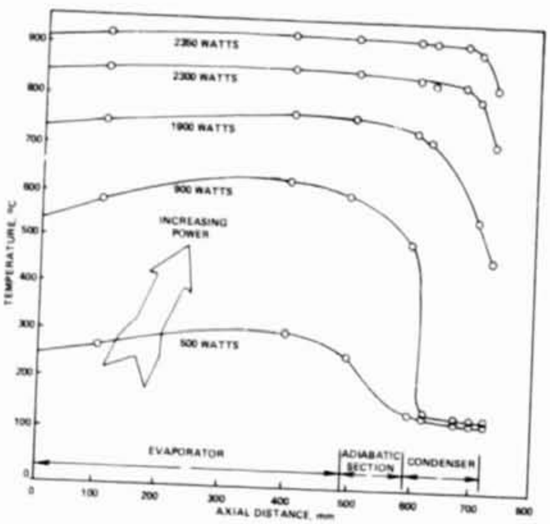

Figure 5. Operating Characteristics of Heat Pipe No. 1 at 10° Inclination

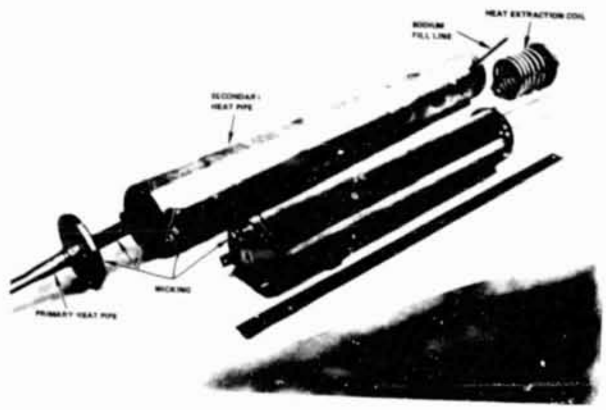

Figure 6. TES Modular Experiment Components

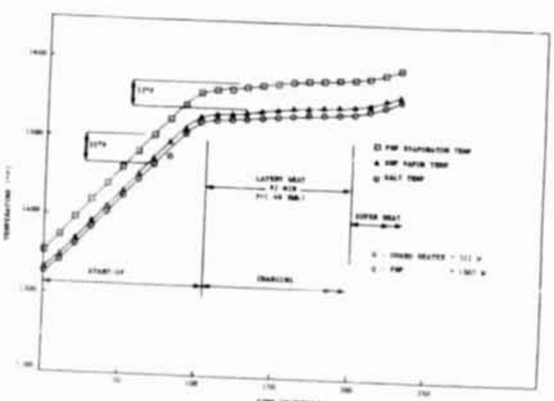

Figure 7. Typical TES Charging Curve for the Modular Experiment

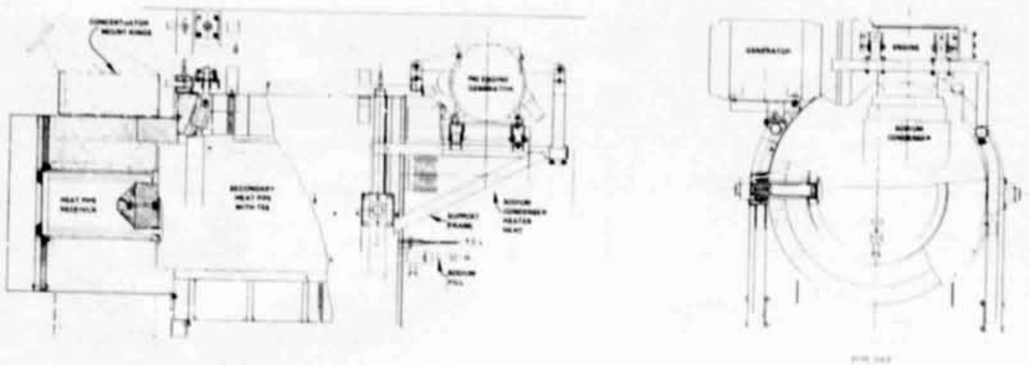

Figure 8. 25 kW_e Prototype HPSR/TES/Engine Generator System

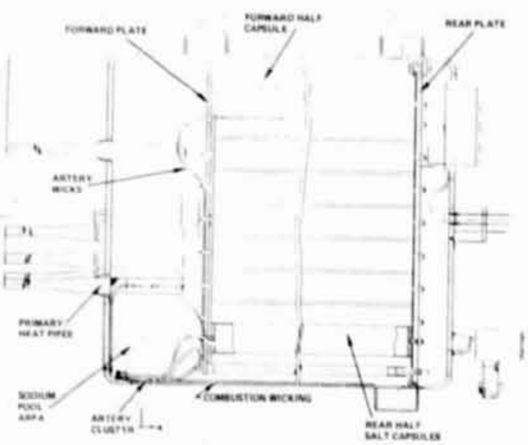

Figure 9. Secondary Heat Pipe Wicking

TABLE I

KEY CHARACTERISTICS OF HPSR SYSTEM

Test Bed Concentrator	
Concentrator Diameter	11 m
Concentration Ratio	2000
Overall Concentrator Efficiency	0.9259
Shaded Concentrator Focal Plane Power	77.0
Solar Receiver	
Aperture Diameter	6.5 in.
Intercept Factor	0.98
Receiver Efficiency	0.908
Power Output	68.5 kW_t
TES Heat Pipe	
TES Material	$67NaF-33MgF_2$
Storage Time (latent + sensible at 66.2 kW_t)	~0.8 hr
TES Efficiency	0.966
TES Operating Temperature Range	1480-1535°F
Power Output	66.2 KW_t
P40 Stirling Engine - Generator	
Nominal HX Temperature	1520°F
Engine Performance (150 Atm He, 1800 RPM, 1520°F)	
Efficiency	0.396*
Power	26.2 kW
Generator Efficiency	0.93
Generator Output	24.4 kW_e
Overall System Efficiency (Solar/Electric)	0.323

* Conservative estimate; 0.43 with engine heat exchanger design for sodium condenser. Overall system efficiency 0.35 with sodium HX